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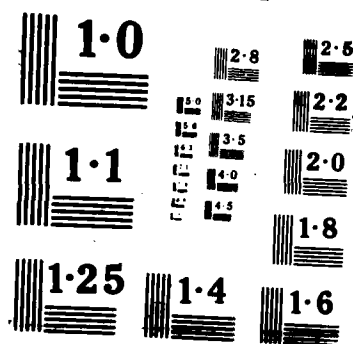   (U) DCW INDUSTRIES INC LA CANADA CA   D C WILCOX DEC 86
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David C. Wilcox

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The primary technical objective of this research project has been to develop and test a new set of constitutive equations suitable for general engineering applications. In accomplishing this objective, particular emphasis has been focused upon predicting rates of departure from and return to equilibrium. Throughout the research in this project, a secondary goal has been to devise our turbulence model equations subject to the self-imposed constraints that the resulting equations pose no special difficulties for conventional numerical procedures, and, to the greatest extent possible, reflect much more of the physics of turbulence than previously attempted in an engineering model.

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DEVELOPMENT OF A COMPLETE

MODEL OF TURBULENCE REVISITED

by

David C. Wilcox

December 1986

Contract DAAG-29-83-0003

Final Report Number DCW-P-29-02

Prepared for

U.S. ARMY RESEARCH ORGANIZATION

Research Triangle Park, North Carolina

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1. OVERVIEW OF WORK ACCOMPLISHED

The primary technical objective of this research project has been to develop and test a new set of constitutive equations suitable for general engineering applications. In accomplishing this objective, particular emphasis has been focused upon predicting rates of departure from and return to equilibrium. Throughout the research in this project, a secondary goal has been to devise our turbulence model equations subject to the self-imposed constraints that the resulting equations pose no special difficulties for conventional numerical procedures, and, to the greatest extent possible, reflect much more of the physics of turbulence than previously attempted in an engineering model.

These primary objectives have been accomplished in this research project in three distinct phases. The first phase focused on reassessing two-equation turbulence models and postulating a new model. Phase One was accomplished in the first year of Contract DAAG-29-83-C-0003. The second phase concentrated upon removing the usual turbulence model assumption that Reynolds stress is proportional to mean strain rate. Removing this assumption was accomplished by postulating a new model known as the multiscale model. Phase Two was accomplished in Year's Two and Three of the Contract. The third phase was dedicated to applying the new multiscale model to unsteady boundary layers. Phase Three was conducted during the fourth and final year of this Contract.

1.1 Phase One (Year One)

During the first year our progress was very rapid. By applying asymptotic methods to the defect layer with adverse pressure gradient, we found very quickly that existing models were obviously going to be inaccurate for boundary layers subjected to adverse pressure gradient. We found that a simple change in dependent variables yields a turbulence model with greatly improved predictive accuracy for such boundary layers. A wide range of numerical applications to attached two-dimensional boundary layers confirmed our asymptotic analysis and thus completed the first step of our overall research plan. Complete details of the first year's research efforts were published as an AIAA paper in January, 1984, viz,

> Wilcox, D.C., "A Complete Model of Turbulence Revisited," AIAA Paper 84-0176 (1984).

1.2 Phase Two (Years Two and Three)

The second step proved far more difficult and, in fact, involved several false starts. Three different approaches were implemented, all of which ultimately were discarded for various reasons. A full year of research was invested in finding out what not to do. As with all such research, the effort was not fruitless. Each approach improved upon the preceding attempt, and finally formulation number four satisfied the original objective.

1

The ultimate model developed is now referred to as the multiscale model. The name is derived from the fact that two distinct energy scales are used to describe the turbulence, one for "small" eddies and one for "large" eddies. Selection of this type of description satisfies another of our original objectives, viz, to incorporate much more of the physics of turbulence into the model than previously attempted. During the third year, we were able to demonstrate that the model accurately describes properties of homogeneous turbulence and two-dimensional boundary layers with adverse pressure gradient for both compressible and incompressible flow conditions. Complete details of the second and third year's research efforts were published as an AIAA paper in January, 1986, viz,

> Wilcox, D.C., "Multiscale Model for Turbulent Flows," AIAA Paper 86-0029 (Jan 1986).

1.3 Phase Three (Year Four)
In our fourth and final year of Contract DAAG29-83-C-0003 we have extended application of the multiscale model to more complex flows. The applications include three Mach 3 shock-separated turbulent boundary layers and a total of nine unsteady turbulent boundary layer computations for a nontrivial range of Strouhal numbers.

Although only a cursory examination of model predictions for separated flows was made, our Navier-Stokes computations produced potentially profound results. We performed Navier-Stokes computations only as an intermediate step toward developing an unsteady boundary layer program. In testing the program, we simulated the flow attending reflection of an oblique shock from a flat plate. We first performed the computation with the two-equation model developed in the first year's research activities. Results were satisfactory with a steady solution developing naturally in time. Then, we repeated the computation with the multiscale model and a provocative thing happened. Consistent with most experimental observations, the flow within and in the wake of the separation bubble was found to be inherently unsteady.

Our unsteady boundary-layer computations offer the first definitive measure of how accurately the multiscale model simulates the physics of turbulent boundary layers. For a wide range of Strouhal numbers, we have more-or-less duplicated the structure of a turbulent boundary layer subjected to a sinusoidally varying adverse pressure gradient. Our two-equation model is far less accurate for these flows. Complete details of the fourth year's research efforts will be published as an AIAA paper in January, 1987, viz,

> D.C. Wilcox, "Advanced Applications of the Multiscale Model for Turbulent Flows," AIAA Paper 87-0290 (Jan 1987).

1.4 Concluding Remarks

As a final comment on the results of our research efforts under Contract DAAG29-83-C-0003 relative to the original objectives, we feel completely justified in claiming that our goal of constructing a "numerically well behaved" model has been accomplished. To justify this claim, we include Table 1 which shows the computing-time increase relative to the two-equation model for four different types of computational procedures.

Table 1. Computing time comparison.

Type of Application	Percent Increase over 2-Equation Model
2-D Boundary Layer	25%
3-D Boundary Layer	40%
Navier Stokes	45%
Unsteady Boundary Layer	45%

2. TECHNOLOGY TRANSFER

Working copies of the two-dimensional/axisymmetric boundary-layer program, EDDYBL, which embodies the multiscale and k-ω two-equation models developed under Contract DAAG-29-83-C-0003 have been installed at the following facilities.

ACA Industries, Inc.
Air Force Office of Scientific Research
Ballistic Research Laboratory
BMO/MYES (Norton Air Force Base)
Carleton University
NASA Ames Research Center
NASA Langley Research Center
North Carolina Agricultural and Technical State University
Office of Naval Research
Physical Research, Inc.
Redstone Arsenal
Rutgers University
Stanford University
University of California, Los Angeles
University of New Mexico
University of Tennessee, Knoxville
University of Tennessee Space Institute

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